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NLC Gamma-Gamma Beam Dump Face Calculations

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NLC Gamma-Gamma Beam Dump Face Calculations

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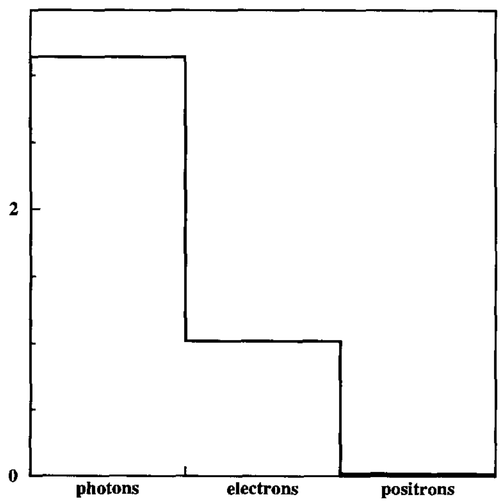
Abstract:

The NLC beam dump face is a thin copper plate. Energy deposition in the copper face has two sources – primary and secondary electromagnetic showers. Primary showers are those where the incoming beam particle initiates an electromagnetic cascade. Secondary showers are those that occur after a nuclear interaction of a beam particle with the copper. An upper limit for the nuclear transmutation rate is also estimated.

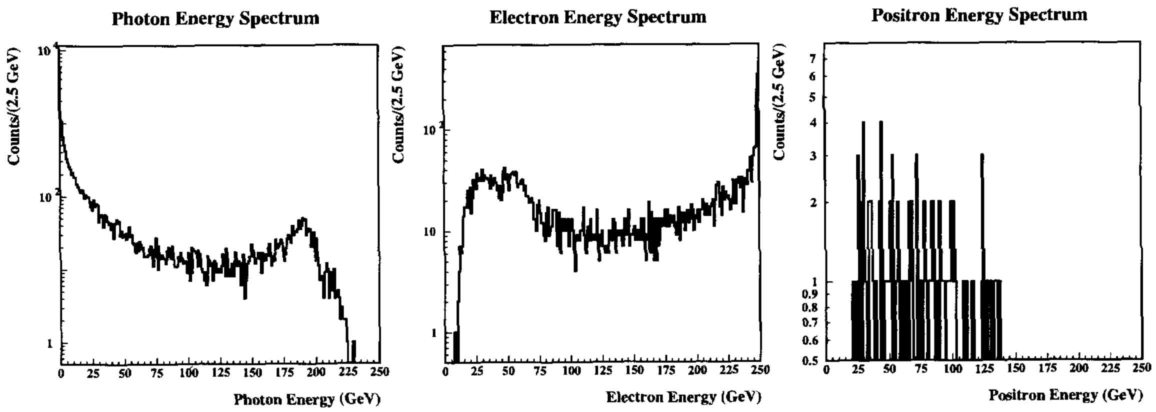
Physical Arrangement

The beam dumps are located 150 m downstream of the interaction point (IP). The dumps are primarily composed of water. The window at the face of the dump is a copper plate. The beams reaching the dump are composed of electrons, positrons and photons modeled in CAIN simulation. A figure showing the normalized composition of the extracted beams as calculated by CAIN for a 250 GeV beam energy and some final focus arrangement is shown below. The units are normalized to the incoming beam intensity, I_0.

Beam Constitution

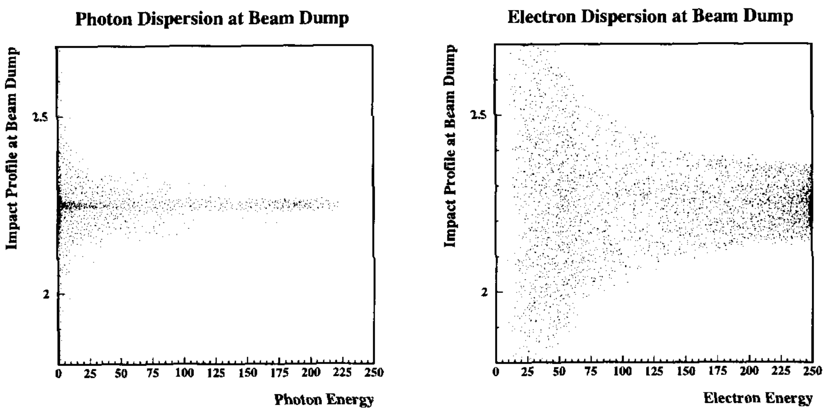


There are 3.14 I_0 photons, 1.02 I_0 electrons and 0.02 I_0 positrons in the exit beam. The energy distribution of each species is shown in the following figures.

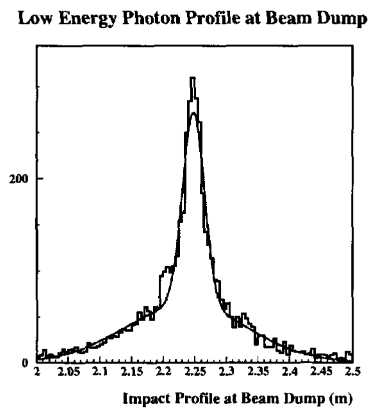


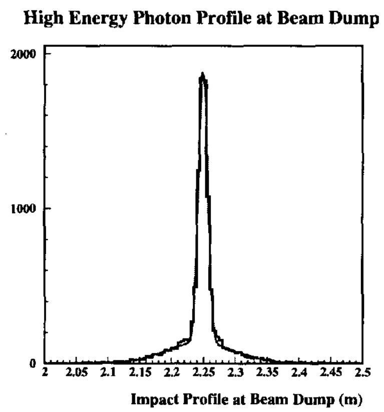
Given the limited statistics of the positrons, we will neglect them for the rest of the calculations.

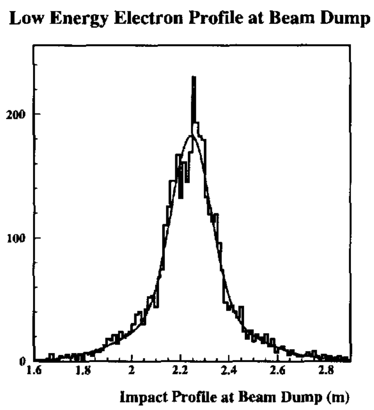
The dispersion of the beams is energy dependent. The following plots show the radial impact position, in meters, of beam particles at the face of the beam dump. The non-zero central value is due to the crossing angle.

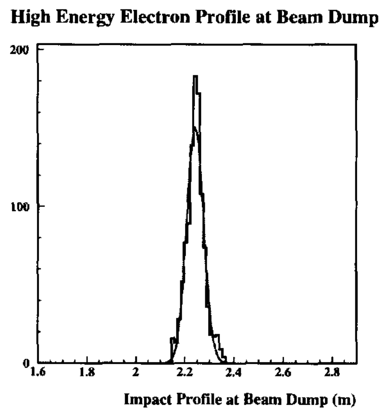


In order to get a reasonable parameterization of the energy dependant profiles, two different energy regions will be used for each species. The photons will be divided at 750 MeV. The low energy sample contains 1.06 I_0 and the high energy sample contains 2.08 I_0. The electrons are divided at 245 GeV. The low energy sample contains 0.81 I_0 and the high energy contains 0.21 I_0. Fits to the impact profiles are shown below.









Except for the high energy electron sample, which was fit with a single gaussian, the profiles were fit using a pair of gaussians. There is no physical reason for using two gaussians, it is just a simple parameterization of the profiles. Below is a summary of the beam at the face of the dump.

Sample Description	Intensity (I_0)	1σ Profile at dump (mm)
HE Photon – narrow component	1.32	7.11
HE Photon – broad component	0.76	54.6
LE Photon – narrow component	0.39	17.3
LE Photon – broad component	0.67	97.1
HE Electron	0.21	34.4
LE Electron – narrow component	0.47	80.6
LE Electron – broad component	0.34	229

Energy Deposition in Primary Cascades

Beam particles arriving at the dump may begin to shower in the copper plate beam dump window. The exact thickness of the window is yet to be determined, however, it will certainly be less than 3mm which is much smaller than a radiation length, $x_0 = 1.43$ cm.

The EGS4 simulation package was used to determine the energy deposition in the copper plate since the general longitudinal shower development equation given in the PDG is known to terribly underestimate the energy deposition profile at small penetration depths. In fact, the parameterization is based on fits to EGS4 results where the data below 2 radiation lengths were omitted to arrive at a reasonable chi squared.

EGS4 was run for three different incident energies (1 GeV, 10 GeV, 100 GeV) and six different copper plate thicknesses (0.5 mm, 1.0mm, 1.5mm, 2.0mm, 2.5mm, 3.0mm) for both electron and photon beams. The energy deposition is summarized in the following tables.

e- Energy (GeV)	0.5mm	1.0mm	1.5mm	2.0mm	2.5mm	3.0mm
1	0.63 MeV	1.3 MeV	2.0 MeV	2.7 MeV	3.5 MeV	4.3 MeV
10	0.63 MeV	1.3 MeV	2.0 MeV	2.8 MeV	3.6 MeV	4.4 MeV
100	0.63 MeV	1.3 MeV	2.0 MeV	2.8 MeV	3.6 MeV	4.5 MeV

γ Energy (GeV)	0.5mm	1.0mm	1.5mm	2.0mm	2.5mm	3.0mm
1	0.016 MeV	0.064 MeV	0.15 MeV	0.26 MeV	0.40 MeV	0.59 MeV
10	0.017 MeV	0.071 MeV	0.15 MeV	0.27 MeV	0.43 MeV	0.62 MeV
100	0.017 MeV	0.069 MeV	0.16 MeV	0.28 MeV	0.42 MeV	0.64 MeV

Energy deposition is nearly energy independent. We choose the central values for an energy independent representation.

Incoming Particle	0.5mm	1.0mm	1.5mm	2.0mm	2.5mm	3.0mm
e-	0.63 MeV	1.3 MeV	2.0 MeV	2.8 MeV	3.6 MeV	4.4 MeV
γ	0.017 MeV	0.068 MeV	0.15 MeV	0.27 MeV	0.42 MeV	0.62 MeV

The electron energy deposition, E_{dep}^{e}, is linear in the copper plate thickness,

$$E_{dep}^{e} = 1.37t \frac{MeV}{mm},$$

and the photon energy deposition, E_{dep}^{γ}, is quadratic in the thickness,

$$E_{dep}^{\gamma} = 0.068t^2 \frac{MeV}{(mm^2)}.$$

In order to complete the primary power deposition, the beam intensity, I_0, must be quantified and included. The baseline NLC will produce beam bunches containing 0.75×10^{10} particles, 90 bunches per train and 120 trains per second. Even though the gamma-gamma IR will see a different bunch structure (twice the bunch size with half the bunch count), the number of electrons coming to either IR is 1.7×10^{14} per second. We can combine the beam intensity with the energy deposition approximations and the exit beam profiles to arrive at the power deposition in the copper plate as a function of the plate thickness, t (mm).

Particle	**1σ Profile (mm)**	**Power Deposition (W)**
Photon	7.11	$2.5\ t^2$
Photon	54.6	$1.4\ t^2$
Photon	17.3	$0.7\ t^2$
Photon	97.1	$1.3\ t^2$
Electron	34.4	7.8 t
Electron	80.6	17.4 t
Electron	229	12.6 t

Energy deposition in the copper plate due to primary cascades occurs at a rate of

$$P = (5.9t^2 + 37.8t)W \ ,$$

where t is the copper plate thickness in millimeters.

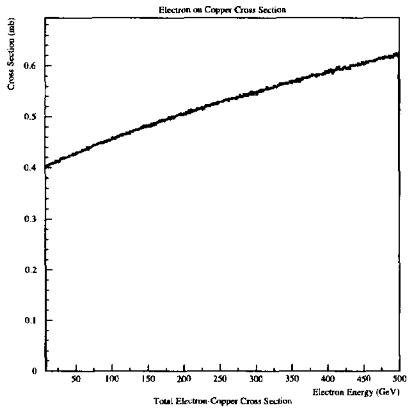
Energy Deposition from Secondary Cascades

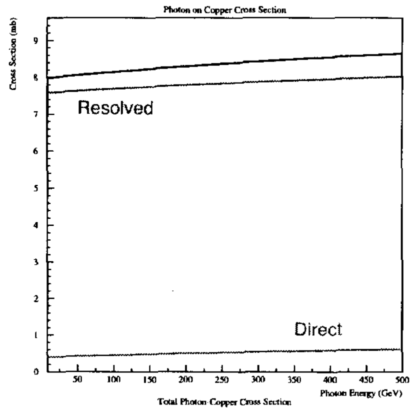
Sometimes a beam particle undergoes a hard interaction with a copper nucleus. The interaction will lead to spray of particles that will subsequently deposit energy electromagnetically into the copper. The energy deposition estimate for these secondary cascades requires knowledge of the electron-copper and photon-copper nuclear cross sections, the number and types of particles produced in the nuclear interactions and the energy deposition for the particle species that emerge from the interaction.

The nuclear cross-sections have been estimated using PYTHIA. Of course PYTHIA does not contain cross sections for copper. We use PYTHIA to calculate proton and neutron cross sections and "build" a copper nucleus from them using a simple counting argument,

$$\sigma_{Cu} = 29 * \sigma_{proton} + (63.5 - 29) * \sigma_{neutron} \ .$$

The cross sections as a function of energy are shown below.





The photon cross section is broken down into its direct and resolved components. Clearly the resolved photon contribution is largest, as expected, and the photon cross section is much larger than the electron cross section. The differences in the neutron and proton cross sections is negligible at these energies. To simplify the energy deposition estimation, we will consider these cross sections energy independent,

$$\sigma_{Cu}^{e} = 500\mu b$$

and

$$\sigma_{Cu}^{\gamma} = 8.3mb \ .$$

The odds that a nuclear interaction will occur for a given particle is a function of the cross section, the copper density and the thickness, and is just the ratio of "presented" cross section (σ times the number of targets, N) and the surface area (Area),

$$P = \frac{\sigma_i N}{Area} = \frac{\sigma_i \dfrac{\rho V N_a}{AW}}{Area} = \frac{\sigma_i \dfrac{\rho t Area N_a}{AW}}{Area} = \frac{\sigma_i \rho N_a}{AW} t = \frac{8.5x10^{-3}}{mm \bullet b} \sigma_i t \ ,$$

where the cross section, σ_i (superscript designates electron or photon), is in barns and the thickness, t, is in millimeters. Multiplying this by the beam intensities yields the nuclear interaction (nuclear transmutation) rates,

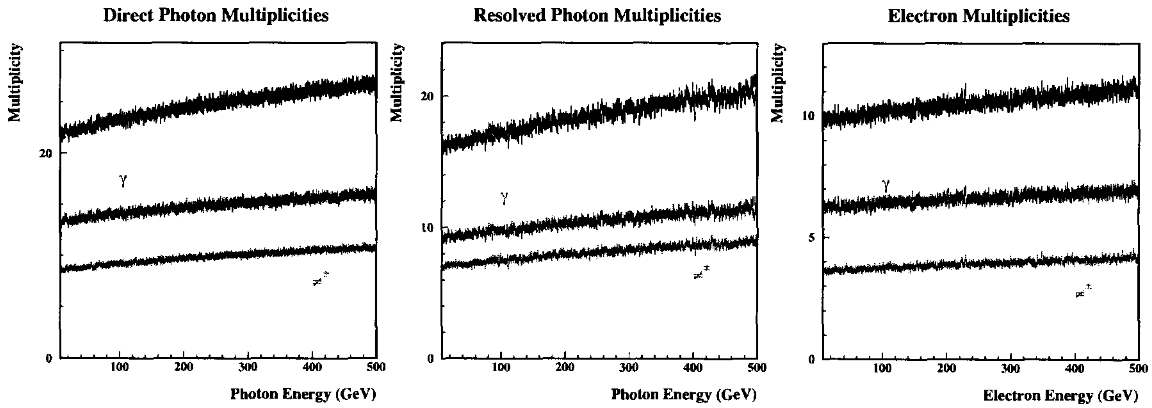
$$R_e = I_e P = \frac{(1.73x10^{14})(8.5x10^{-3})(500x10^{-6})}{mm} t\left(\frac{1}{s}\right) = \frac{7.3x10^{8}}{mm} t\left(\frac{1}{s}\right) ,$$

and for the photons,

$$R_\gamma = I_\gamma P = \frac{(5.3x10^{14})(8.5x10^{-3})(8.3x10^{-3})}{mm} t\left(\frac{1}{s}\right) = \frac{3.7x10^{10}}{mm} t\left(\frac{1}{s}\right) .$$

The photon nuclear absorption rate is a factor of 20 larger than that of the electron.

The number of particles that emerge from these interactions is also estimated using PYTHIA. The following plots show the average multiplicity as a function of incoming energy for direct photons, resolved photons and electrons.



The first thing to notice is that the multiplicity is well approximated as independent of energy. This is to be expected since the center of mass energy goes as the square root of the beam energy. The following table lists the multiplicity approximations.

Beam Type	**γ multiplicity**	**π multiplicity**	**Total multiplicity**
γ (direct)	15	10	25
γ (resolved)	10	8	18
e-	6	4	10

To arrive at a single set of multiplicities for the photon, the direct and resolved multiplicities must be weighted by their cross sections. Since the resolved photon cross section is 19 times the direct photon, we will simply use the resolved photon multiplicities in the remainder of the calculation.

The production rate of photons, Gγ, and hadrons, Gπ, from hard interactions is calculated using the nuclear interaction rates and the production multiplicities. Since the photon nuclear interaction rate is 20 times larger than the electron and the multiplicities are nearly a factor of two larger, we approximate the total production rates by those of the photons.

$$G_\gamma = 10\frac{7.3x10^8}{mm}t\left(\frac{1}{s}\right) = \frac{7.3x10^9}{mm}t\left(\frac{1}{s}\right),$$

and

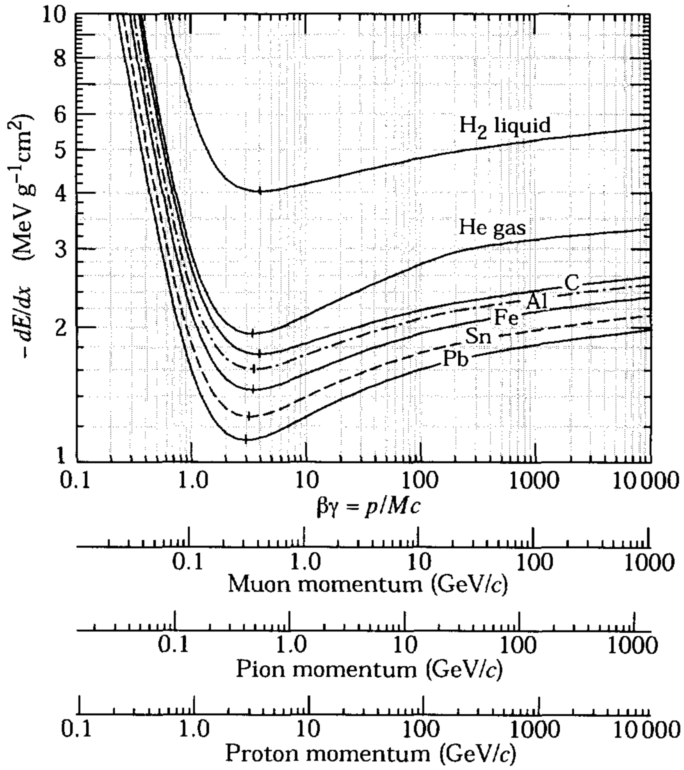
$$G_\pi = 8\frac{3.7x10^{10}}{mm}t\left(\frac{1}{s}\right) = \frac{3.0x10^{11}}{mm}t\left(\frac{1}{s}\right),$$

again, t is the copper plate thickness in millimeters.

The energy deposition rate is just the production rate multiplied by the mean energy deposition. If we extend the photon deposition model developed earlier and assume that the mean distance each secondary photon traverses is t, we find

$$E_{dep}^{\gamma\,\sec} = 0.068t^2 \frac{MeV}{(mm^2)} \bullet \frac{7.3x10^9}{mm} t\left(\frac{1}{s}\right) = \frac{5.0x10^8}{mm^3} t^3\left(\frac{MeV}{s}\right) = \frac{8.0x10^{-5}}{mm^3} t^3(W) \,,$$

which is several orders of magnitude smaller than the energy deposited by the primary cascades for small t. We can safely neglect this contribution. The pions produced in the hard interaction will primarily lose energy through ionization in the copper. The rate of energy loss for several projectiles through various materials is shown in the figure below (extracted from PDG).



If we assume that the average dE/dx for the pions emerging from the nuclear interactions is 100 MeV $g^{-1}cm^2$ (a gross overestimate), then the rate at which the pions deposit energy would be (assuming all the pions traverse t mm of copper),

$$E_{dep}^{\pi\,\sec} = 100 \frac{MeV}{g/cm^2} \bullet 12.86 g/cm^2 \bullet \frac{t}{14.3mm} \bullet \frac{3.0x10^{11}}{mm} t\left(\frac{1}{s}\right) = \frac{4.3}{mm^2} t^2(W) \,,$$

where t is the copper plate thickness in millimeters. Recall that it is the photon beam that overwhelmingly interacts with the copper nuclei and if one assumes that there is little (no) energy dispersion brought about by the secondary cascade (certainly a good approximation at the higher energies), we can use the photon profiles to finalize the exaggerated secondary energy deposition estimation:

Beam Particle	1σ Profile (mm)	Power Deposition (W)
Photon	7.11	1.8 t^2
Photon	54.6	1.0 t^2
Photon	17.3	0.5 t^2
Photon	97.1	1.0 t^2